Engineering Laser Systems for Aerospace & Defense Applications

Nicholas Sawruk, Fibertek, Inc.
The OSA Laser Systems Technical Group Welcomes You!

ENGINEERING LASER SYSTEMS FOR AEROSPACE AND DEFENSE APPLICATIONS

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Technical Group at a Glance

• **Focus**
  • This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications.

• **Mission**
  • To benefit *YOU*
  • Webinars, e-Presence, publications, technical events, business events, outreach
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Today’s Webinar

**Engineering Laser Systems for Aerospace and Defense Applications**

**Nicholas Sawruk**
Fibertek, Inc.

**Speaker’s Short Bio:**
Nicholas Sawruk is the Director of Laser & Optical Engineering at Fibertek, Inc. Mr. Sawruk has over 15 years of experience developing, designing, integrating, and testing laser/EO systems. His support experience includes the NASA Ice Cloud and Elevation Satellite laser systems where he served as the principal investigator and program manager of a high reliability laser system for a national asset space satellite. Over his career, Mr. Sawruk developed, matured and delivered state of the art laser systems including chemical, gas, solid state and fiber lasers for a wide range of defense and science sensing missions. He received a bachelors of science degree in Physics and Mathematics from the United States Air Force Academy and a masters of science degree from the University of New Mexico.
ENGINEERING LASERS FOR MILITARY AND SPACE APPLICATIONS

2020 OSA WEBINAR
17 JULY 2020

Nicholas W. Sawruk – Director of Laser & Optical Engineering
nsawruk@fibertek.com
Fibertek Active EO Systems for Space & Military Applications

CALIPSO (launched 2006)
12+ years 24/7 operation (3-year design life)

ICESat-2 (launched 2018)
The only TRL9 multi-Watt, multi-kHz, high-efficiency nanosecond space laser.
>500 Gshots to-date – more than any other NASA space laser

Military Lasers
LIDAR illuminators, designators, range-finders, and infrared counter-measures

Fibertek has engineered lasers and active E-O systems for space and military applications for ~35 years
Laser-based sensors are critical technologies for military & aerospace missions
Design priorities for military and aerospace lasers are more driven by reliability, mission performance, environments, and SWaP (size, weight, & power) vs. commercial/industrial lasers.

<table>
<thead>
<tr>
<th>Laser Properties</th>
<th>Military &amp; Aerospace</th>
<th>Industrial &amp; Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Motivation</td>
<td>Priority</td>
</tr>
<tr>
<td>Power</td>
<td>Extends range for standoff sensors &amp; effects</td>
<td>High</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Platforms have limited power and/or heat dissipation</td>
<td>High</td>
</tr>
<tr>
<td>Reliability</td>
<td>Mission criticality and difficult service &amp; replacement</td>
<td>Highest</td>
</tr>
<tr>
<td>Compact size</td>
<td>Platforms (esp. air &amp; space) are highly sensitive to size &amp; weight</td>
<td>High</td>
</tr>
<tr>
<td>Conduction (or forced air) cooling</td>
<td>Reduces size &amp; weight, compatibility with environments</td>
<td>Med</td>
</tr>
<tr>
<td>Cost</td>
<td>Important, after high-priorities are met</td>
<td>Med</td>
</tr>
<tr>
<td>Mission-specific performance</td>
<td>Leading-edge performance is often required</td>
<td>High</td>
</tr>
<tr>
<td>(wavelength, tailored waveforms, etc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission-specific environments</td>
<td>Operability is required over a wide range of conditions</td>
<td>High</td>
</tr>
<tr>
<td>Modularity/versatility</td>
<td>Frequently compromised for mission-specific needs</td>
<td>Low</td>
</tr>
</tbody>
</table>
Mission Enabling Laser System Examples

**WALES, the Airborne Demonstrator for a Water Vapor Differential Absorption LIDAR in Space**

- 4-λ system at specific & non-standard wavelengths (~935 nm)
- Single frequency Optical Parametric Oscillator
- 45 mJ Energy @ 100 Hz
- >500 hours of airborne operation

**Aeolus – UV Doppler Wind Lidar Frequency Stabilized, High Energy UV Laser in Space**

- Atmospheric wind profiles form the ground to the lower stratosphere on global scale
- 50.5 Hz, >100 mJ, 20 ns @ UV
- 1.9 B shots in 15-months of operation in space

**NASA GSFC ASCENDS Fiber MOPA for CH₄ & CO₂ Sensing**

- Rapidly-tunable single frequency output at specific λ
- 450 µJ, 7.5 kHz and > 20 dB polarization extinction ratio
- Compact & survive the rigors of launch & space applications

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Examples demonstrate a range of mission specific requirements in terms of wavelength, linewidth & performance in diverse operational environments and all with a priority on minimal SWaP
ICESat-2 (launched 2018)
- Key challenge: high-reliability design for 24/7 operation over 3 years & >1 Trillion laser shots
- >10x shot count of other remote-sensing space lasers

Airborne DIAL
Key challenges:
- Precise frequency control in an airborne environment
- Advancing the technology toward space

Pulsed fiber lasers
Key challenges:
- Peak-power (pulse energy) performance
- Component qualification (temperature & radiation)

3 examples show how design challenges have been met to deliver reliable lasers for aerospace missions.
ICESat-2 Laser Transmitter

Example of a high reliability laser transmitter for a 3-year duration space mission.
• ICESat-2 carries a single instrument – the Advanced Topographic Laser Altimeter System (ATLAS).
  • ATLAS measures the travel times of lasers pulses to calculate the distance between the spacecraft and Earth’s surface
  • ATLAS carries two redundant lasers, one primary and one backup.

• The four ICESat-2 science objectives are
  • Measure melting ice sheets and investigate how this effects sea level rise
  • Measure and investigate changes in the mass of ice sheets and glaciers
  • Estimate and study sea ice thickness
  • Measure the height of vegetation in forests and other ecosystems worldwide
# ICESat-2 Laser Driving Requirements & Resulting Enabling Capability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Flight Lasers</th>
<th>Enabling Lidar Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (µJ)</td>
<td>250-900</td>
<td>250-1,370</td>
<td>Required pulse energy for multi-beam (6x) altimeter per laser shot, i.e. single output beam is split into 6 beams providing dense cross track sampling required for surface slope measurements.</td>
</tr>
<tr>
<td>Pulse Rate (kHz)</td>
<td>10</td>
<td>10</td>
<td>Fine ground sampling distance, measurements every 70 cm.</td>
</tr>
<tr>
<td>Pulse Width (ns)</td>
<td>1.5</td>
<td>&lt;1.3</td>
<td>Fine height measurement resolution.</td>
</tr>
<tr>
<td>Divergence (µrad)</td>
<td>&lt;130</td>
<td>91</td>
<td>&lt;1.5x diffraction limited BQ – Minimal illuminated spot on the ground.</td>
</tr>
<tr>
<td>Tunable Wavelength (nm)</td>
<td>532.27±0.015</td>
<td>532.27±0.015</td>
<td>Absolute wavelength tunable to match etalon receiver transmission – minimizing background contributions.</td>
</tr>
<tr>
<td>Linewidth (pm)</td>
<td>&lt;30</td>
<td>&lt;5</td>
<td>Enables a narrow linewidth receiver filter – minimizing background contributions.</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;5%</td>
<td>8.2%</td>
<td>High efficiency – reducing spacecraft thermal management &amp; power distribution requirements.</td>
</tr>
<tr>
<td>Operational Run-Time</td>
<td>3.5 years</td>
<td>Life test Lasers (&gt; 1 T shots)</td>
<td>Demonstrate reliability required for long duration lidar missions – allows for long term trend measurements.</td>
</tr>
</tbody>
</table>
ICESat-2 Laser Overview

- Integrated and ruggedized packaging – single unit with power and command inputs and 532 nm photons out.
  - 30 cm x 50 cm x 15 cm, 19 kg
  - Flexure mounted laser system with hermetically seal laser module and vented electronics module in a single unit.

- ICESat-2 lasers are State-of-the-Art space qualified lasers simultaneously requiring short pulse width, high average power, frequency tunability, near diffraction limited beam quality and a minimum life-time shot count of 1 Trillion shots.

ICESat-2 mission requires ~3-orders of magnitude more laser shots, with the most stringent wavelength control and temporal pulse width requirements of any NASA spaceflight laser altimeter to date.
ICESat-2 Laser Design Features

- Short, electro-optical Q-Switched oscillator generating key performance:
  - Short pulse widths, diffraction limited BQ, 10 kHz PRF, and wavelength tunable w/ narrow linewidth.

- End-Pumped amplifier chain
  - Excellent Efficiency (40% Optical to Optical)
  - Preserves beam quality ($M^2 \sim 1.3$)
  - Enable by high brightness fiber coupled diode pumps.

- Pulsed-Pumped w/ variable phasing and pump duration
  - Energy tuning from 250 µJ to > 1,000 µJ
  - Constant thermal loading, i.e. minimal changes in beam divergence, pointing, & position.

- High efficiency frequency conversion via critically phased match LBO

- Wall Plug Efficiency @ Full Energy: >7%
A test centric diode laser space certification program consisting of several key phases including a technology plausibility study, component and LDM pedigree reviews, and environmental acceptance was developed and successfully executed.

This program is well documented & adaptable to future space missions.

Supply Chain Management of Optical Components for Space

- Space qualified optical components are not a commodity, lacking industry accepted standardized processes and/or certification procedures common to electronic components for space applications.
  - Typically small companies with relatively high turn over and consolidation rates complicate reuse of the developed supply chain.
  - Optical component supply chain management is challenging requiring a balance between design updates and maintaining an established process.

- Optical coating technology, lot certification and qualification.
  - Vendor survey & down select based on coating requirements.

- Faraday Rotators compatible with environments were not commercially available.
  - Incompatible materials, not vacuum compatible and not robust to GEVS random vibe.
  - Worked closely with the rotator vendor and collaboratively upgraded the rotator design and executed a qualification program.

Fibertek successfully developed screening procedures and guided designs of key optical components from commercial vendors.
• Laser was initially operated at 600 µJ for several days. The output energy was decreased to 450 µJ due to better than expected signal returns.

• 2.6% drop in 532 nm pulse energy over 18 months of operation is better than anticipated (~2x less than early life test lasers) indicating the contamination mitigation protocols are successful.
Space-Based Laser Lessons Learned

• Mature technologies are required for the rapid advancement of technology readiness levels (TRL) required on recent programs.

• A robust and comprehensive test program, in relevant environments, early in the program surfaces design issues and allows for the implementation of corrective actions.

• Mitigation of contamination sources is a key to long term reliability.

• De-rating the top-level system and sub-systems results in a higher reliability system.

• Process rigor and discipline during all phases (design, procurement, component processing, system integration and test, etc.) of the program are required for consistent high reliability laser systems
  • Culture of building high-reliably and well documented space systems.
Airborne Differential Absorption Lidar Transmitter

Single frequency laser operating at a specific & non-standard wavelength with >1000:1 spectral purity in an airborne environment.
Airborne Differential Absorption Lidar

- Integrated path differential absorption (IPDA) measurement between transmitted energy signal and surface return at on-line (absorbed) and off-line (unabsorbed) wavelengths.
- Combined lidar profiles of water vapor, methane, aerosols and clouds to better understand weather & dynamics.

The Water Vapor Laser is based on an injection-seeded Nd:YAG master-oscillator power-amplifier architecture operating at a wavelength of 1064 nm.

This IR radiation is then frequency doubled to 532 nm and used to optically drive an injection-seeded optical parametric oscillator (OPO) operating at the 935 nm water vapor absorption line.
Operation in Airborne Environment

• The primary environmental impact to the performance of the Water Vapor transmitter is optical misalignment induced by vibration.

• Optical misalignment negatively impacted output power, beam pointing, and spectral purity – three parameters fundamental to any absorption lidar system.

• Three major updates mitigated the laser performance degradation while operating under a dynamic environment.
  • Decouple and flexure mount the internal laser cold plate from the laser optical bench.
  • Increase the stiffness of the optical bench increasing the frequency of the first resonator mode from 250 Hz to 365 Hz.
  • Updated laser resonator design with significantly reduced alignment sensitivity.
Key Laser Performance

• The OPO produced a high-quality spatial pulse with an $M^2$ value of <1.2 and maintained a near transform spectral width of ~40 MHz, well within the 70 MHz objective.

• Preliminary airborne flights were successful.
Fiber Lasers

Examples of space-qualified laser systems for high bandwidth and long range optical communication.
Fiber Laser Transmitters

• Advantages of Fiber Lasers
  • Spatial confinement → signal brightness is maintained over long distance, improving beam quality
  • Distributed gain → low-gain ions (ytterbium, erbium, & thulium) can achieve significant gain (typically 20-30 dB per stage) with meter-length fibers
  • Distributed heat load → simplified thermal management in comparison to solid-state lasers
  • High efficiency → above advantages lead to deep saturation of lasers and amplifiers, resulting in high efficiency (>40% E-O in Yb:fiber, >20% in Er:fiber or Tm:fiber)

• Disadvantages
  • Nonlinear behavior → spatial confinement leads to accumulated nonlinear behavior (SBS, SRS, FWM, SPM, XPM, etc.)
  • Limited peak power → Fibertek has demonstrated >1 MW peak power in Yb:fiber, but practical limits in fielded systems are typically ~50-100 kW
  • Radiation hardness

Tremendous advances have been made in fiber lasers, pushing average power per diffraction-limited aperture to ~3-4 kW for terrestrial – but peak power performance is limited and power and thermal management for space remain a challenge
Examples of TRL-6+ Fiber Lasers for Space

Fibertek has built engineered space-qualifiable fiber laser & amplifier systems at power levels from <1 to >100 W average power, up to 100 kW peak power, CW & pulsed, and at 1 um, 1.5 um, and 2 um wavelengths.

20 W CW 1.5 um fiber amplifier for NASA Ascends

Size: 14” x 8.5” x2”

100 W CW 1.9 um Tm:fiber laser will be TRL5+ in 2019. Photo shows housing & components in vibration testing.

A 50 W pulsed 1.5 um fiber amplifier is also being developed for deep space communications, and will use similar packaging.

Size: 11” x 14” x5”

6 W PPM transmitter for deep-space laser communications
15% E-O efficiency
>1 kW peak power

Size: 10” x 8” x 2.4”
Weight: 7.5 lbs.
- High power 1.5 µm fiber-laser developed for high bandwidth, wavelength multi-plexed, deep-space optical communication links.
- High-efficiency, high-power performance is consistent with design predictions.
- Results show the same average power performance for a single-channel and multi-channel output, enabling flexible implementation to optimize data rates in deep space.
### Component Qualification: Comparison with Telcordia

<table>
<thead>
<tr>
<th>Environment Specification</th>
<th>Typical Military</th>
<th>Typical Space Flight</th>
<th>Commercial Telecom</th>
<th>Design Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference standard or document</td>
<td>MIL-STD-810G</td>
<td>NASA GEVS</td>
<td>Telcordia</td>
<td></td>
</tr>
</tbody>
</table>
| Temperature                       | Mission-dependent, -75°C to +85°C in extreme cases | Mission-dependent, -20°C to 50°C is a common survival temp | -40°C/min to +85°C/max | - Adhesives & seals must maintain integrity over temperature  
- CTE-matching for critically-aligned components  
- Actively control temperature-sensitive optics & electronics |
| Thermal shock                     | ~30°C/min or greater | <=30 C/min typical  | ΔT = 100°C/sec     | Commercial thermal shock (ice & boiling water) for Telcordia components is more severe |
| Pressure / Altitude               | Up to 70,000 ft. | Vacuum-compatible    | NA                 | Cleanliness of optics, photochemistry, and optical/electrical breakdown all must be considered |
| Moisture and humidity             | RH ≤ 90%         | N/A                  | RH 85%/85°C        | Sealed enclosures may be the most effective remedy                                        |
| Random Vibration                  | >20 gRMS in extreme tactical cases | ~14 gRMS (non-operating) | 20 g peak          | - Survival: mounting & positioning must be maintained through vibe (e.g. space launch)  
- Operational: design to maintain critical alignments & beam-pointing can be very challenging |
| Radiation                         | N/A              | Mission Dependent Few kRad to MRad | N/A                | - Space-rated electronics → expensive, long-lead  
- Space-rated laser optical components don’t generally exist → radiation susceptibility testing is typical for space-laser programs |

**Military lasers:** Design driven significantly by temperature & vibration

**Space lasers:** Launch vibration & radiation are added design constraints

**Commercial:** Commercial standards can be useful in selecting components, but do not represent qualification for most military & space environments.
Rapidly growing utility of fiber lasers in space is leading to a growing catalog of qualified components.

### Active components
- **Seed laser diodes**
  - Pre-screening qualification if need
  - Qualifiability per design, material, and process
  - Typically Telcordia qualified with multiple supplier options
- **Low-power pump laser diodes**
  - Mature package design and process
  - Typically Telcordia qualified, high reliability device
- **High power pump laser diodes**
  - Designed for industrial applications
  - Not typically Telcordia qualified
  - Some test data for space (performed by suppliers, Fibertek, NASA, and/or others)
- **Fiber-optic modulators**
  - Some limited space qualification data from ESA/NASA
  - Details of qualification testing is not widely available

### Passive components
- **Fused fiber optic components**
  - Typically Telcordia-qualified, very high reliability components
  - Assuming qualification per similarity is reasonable (similar material, design, and process)
- **Fiber pigtailed micro-optics components**
  - Typically Telcordia qualified, high reliability components
  - Assuming qualification per similarity is reasonable (similar material, design, and process)
- **High power high strength fiber splices**
  - Splice joints are considered as components from viewpoint of reliability
  - Splice process must be qualified & applied to fiber-based systems

Radiation: data is very limited on radiation susceptibility of fiber-optic components, and qualification testing is typically required.
• Laser systems and technologies have an enabling role in LIDAR-based remote sensing systems in military and aerospace communities.

• Lasers for aerospace applications pose a unique set of challenges including harsh environments, limited volumes, power and thermal capacity of platforms.

• Several examples of lasers transitioned from the lab to operational environments were presented enabling new capabilities in lidar and communication systems.